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## Charmonium spectroscopy at *BABAR*

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### Abstract

The charmonium-like states,  $Y(4260)$ ,  $Y(4350)$ , produced via initial state radiation, as well as the  $X(3872)$ , and  $Y(3940)$ , produced in  $B$  meson decays from the *BABAR* B-factory are reviewed. These mesons do not seem consistent with conventional charmonium models, and several alternate hypotheses have been proposed to explain these new discoveries.

### 1 Introduction

Several charmonium-like states have been discovered recently at the BELLE and *BABAR* B-factories. These new states have been observed in  $e^+e^-$  initial state radiation (ISR) interactions or in  $B$ -decays. The relevant Feynman diagrams representing ISR production and  $B$ -decay are shown in Fig. 1. In ISR events, a real photon is emitted from the incoming electron or positron

and subsequently the electron and positron annihilate to yield a virtual photon ( $\gamma^*$ ) which couples to a  $c\bar{c}$  system with c.m. energy lower than the nominal value, and thus charmonia can be produced. In  $\bar{B}$ -decay, a  $W^-$  from the  $b$ -quark yields an  $s\bar{c}$  system; the  $\bar{c}$  combines with the  $c$  quark from  $b$  decay to produce a charmonium state, while the  $s$  quark and  $\bar{q}$  spectator yield a strange meson.

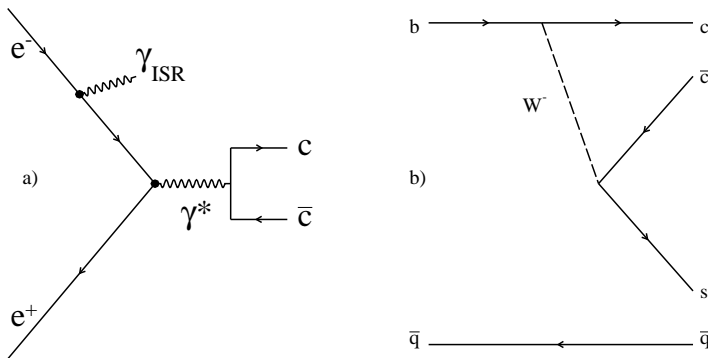


Figure 1: *Feynman diagrams representing charmonium production via a) ISR, b)  $\bar{B}$  decay.*

The discovery of the charmonium-like state  $X(3872) \rightarrow J/\psi\pi^+\pi^-$  was reported by the BELLE collaboration <sup>1)</sup>, and confirmed by the CDF <sup>2)</sup>, D0 <sup>3)</sup>, and BABAR <sup>4)</sup> experiments. Since then several charmonium-like states have been discovered at the  $B$ -factories, however they do not seem consistent with conventional charmonium spectroscopy. Alternative explanations for these states have been proposed, such as molecules, 4-quark states, hybrids, etc.

In this report, we review briefly the latest results from the BABAR experiment concerning four of these charmonium-like states.

## 2 The $Y(4260)$

The  $Y(4260) \rightarrow J/\psi\pi^+\pi^-$  was discovered by BABAR in the ISR reaction  $e^+e^- \rightarrow \gamma_{ISR}J/\psi\pi^+\pi^-$  <sup>5)</sup> using  $233 \text{ fb}^{-1}$  of data, where detection of the ISR photon was not required. The  $J/\psi\pi^+\pi^-$  mass distribution is shown in Fig. 2, where in the sub-figure a broader mass region shows the peak due to

$\psi(2S) \rightarrow J/\psi \pi^+ \pi^-$ ; an enhancement is observed at  $\sim 4.26 \text{ GeV}/c^2$ . The mass region  $3.8 < m_{J/\psi \pi^+ \pi^-} < 5 \text{ GeV}/c^2$  is fitted with a Breit-Wigner signal function and a second order polynomial background. The background from  $J/\psi$  side-band does not show any peaking structure. The number of signal events extracted from the fit is  $125 \pm 23$ , the mass is  $M_Y = 4259 \pm 8_{-6}^{+2} \text{ MeV}/c^2$ , and the width is  $\Gamma_Y = 88 \pm 23_{-4}^{+6} \text{ MeV}$ . The branching fraction obtained is  $\Gamma_{Y,ee} * BF(Y(4260) \rightarrow J/\psi \pi^+ \pi^-) = 5.5 \pm 1.0_{-0.7}^{+0.8} \text{ eV}$ . At *BABAR*, no evidence was found for the processes  $Y(4260) \rightarrow \phi \pi^+ \pi^-$  <sup>6)</sup>,  $Y(4260) \rightarrow D \bar{D}$  <sup>7)</sup>, and  $Y(4260) \rightarrow p \bar{p}$  <sup>8)</sup>. A search for the  $Y(4260)$  resonance in  $B$  decay was carried out, and a  $3\sigma$  effect was observed <sup>9)</sup>.

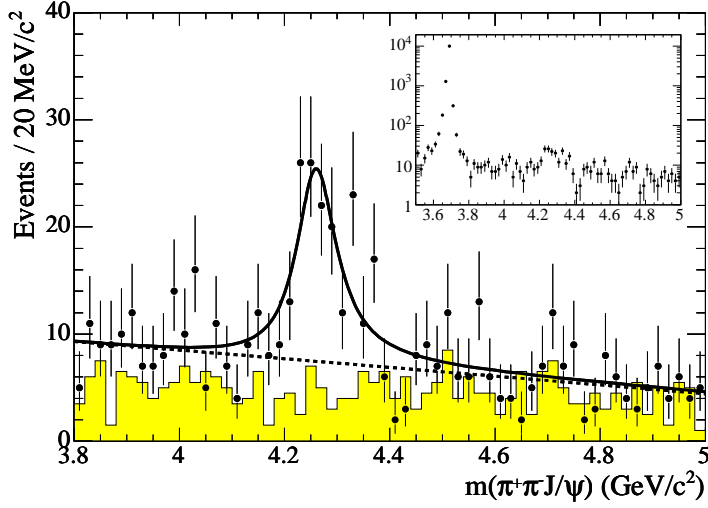


Figure 2: The  $J/\psi \pi^+ \pi^-$  invariant mass distribution in the range  $3.8 - 5.0 \text{ GeV}/c^2$ . The dots represent the data, the filled histogram shows the background from the  $J/\psi$  side-bands, the solid curve represents the fit result and the dashed line shows the background.

### 3 The $Y(4350)$

In *BABAR*, a search for  $Y(4260) \rightarrow \psi(2S) \pi^+ \pi^-$  yielded instead evidence for a broad structure near  $\sim 4.3 \text{ GeV}/c^2$  <sup>10)</sup>. This enhancement is not consistent

with the  $Y(4260)$  state. In Fig. 3, the  $2(\pi^+\pi^-)J/\psi$  invariant mass is shown for the data (dots) and for the background (shaded histogram). The data points are fitted with a Breit-Wigner signal function with fixed mass and width <sup>5)</sup> (dashed line), and again with mass and width as free parameters. The latter fit yields mass  $m = 4324 \pm 23 \text{ MeV}/c^2$ , and width  $\Gamma = 172 \pm 33 \text{ MeV}$  (statistical errors only). The  $Y(4350)$  was confirmed by BELLE <sup>11)</sup>.

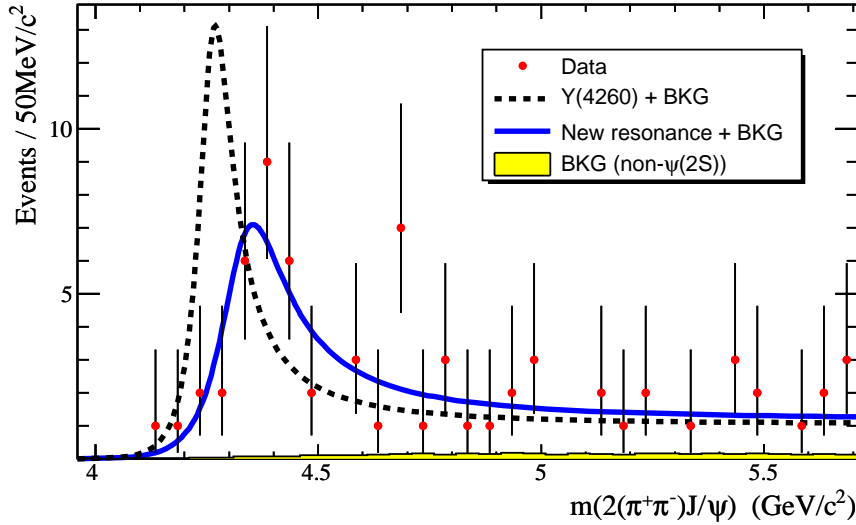


Figure 3: The  $2(\pi^+\pi^-)J/\psi$  invariant mass spectrum. The dots indicate the data and the shaded histogram represents the background. The solid curve shows the fit result with free mass and width parameters, while the dashed curve is obtained with the mass and width fixed to their  $Y(4260)$  values <sup>5)</sup>.

#### 4 The $X(3872)$

The  $X(3872)$  discovered by BELLE <sup>1)</sup> was the first of the new charmonium-like states. Later CDF <sup>2)</sup>, D0 <sup>3)</sup>, and BABAR <sup>4)</sup> confirmed the BELLE observation. In BABAR, a data sample of  $211 \text{ fb}^{-1}$  was analyzed to obtain the  $J/\psi\pi^+\pi^-$  invariant mass in the region  $3.8 - 3.95 \text{ GeV}/c^2$  separately for charged and neutral  $B$ -candidates as shown in Fig. 4. The dots represent the data and the shaded histograms represent background. For charged  $B$  decay (Fig. 4(a)),

a clear enhancement is observed for  $m_{J/\psi\pi^+\pi^-} \sim 3870 \text{ GeV}/c^2$ . Statistically consistent behavior is observed for the neutral mode (Fig. 4(b)). The  $X(3872)$  invariant mass obtained from the charged (neutral)  $B$ -mode is  $m = 3871.3 \pm 0.6 \pm 0.1$  ( $3868.6 \pm 1.2 \pm 0.2$ )  $\text{MeV}/c^2$ , and the corresponding branching fraction values are  $\mathcal{BF}(B^- \rightarrow X(J/\psi\pi^+\pi^-)K^-) = (10.1 \pm 2.5 \pm 1.0) \times 10^{-5}$  and  $\mathcal{B}(B^0 \rightarrow X(J/\psi\pi^+\pi^-)K^0) = (5.1 \pm 2.8 \pm 0.7) \times 10^{-5}$  at 90% C.L.

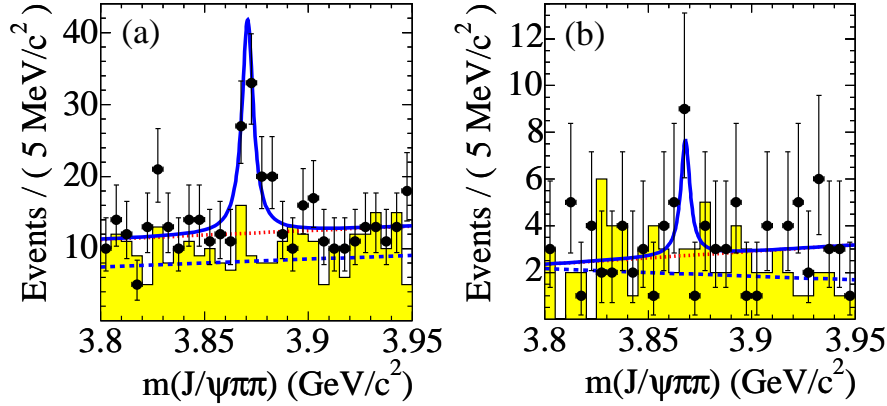


Figure 4: The  $J/\psi\pi^+\pi^-$  invariant mass distributions for charged (a) and neutral (b)  $B$  decay from *BABAR*. The dots represent the data, while the shaded histograms represent side-band background. The solid curves show the fit results, the dashed lines show combinatorial background, and the dotted lines represent the sum of combinatorial and peaking background contributions.

In *BABAR*, no evidence for a charged partner of the  $X(3872)$  was found<sup>12)</sup>, and so it is assumed that the  $X(3872)$  has  $I = 0$ . Also *BABAR*<sup>13)</sup> has confirmed the *BELLE* observation<sup>14)</sup> of  $X(3872) \rightarrow J/\psi\gamma$ . In Fig. 5 we show the  $J/\psi\gamma$  mass distribution obtained from *BABAR*, and a clear enhancement is observed at the  $X(3872)$  mass. It follows that the  $X(3872)$  has positive  $C$ -parity.

Later both *BELLE*<sup>15)</sup> and *BABAR*<sup>16)</sup> have found evidence for the decay mode  $X(3872) \rightarrow \bar{D}^{*0}D^0$ . In Fig. 6, we show the  $\bar{D}^{*0}D^0$  invariant mass as reported by *BABAR*. A clear enhancement near threshold is observed. The measured mass values from *BELLE* and *BABAR* are  $3875.2 \pm 0.7^{+0.9}_{-1.8} \text{ MeV}/c^2$  and  $3875.1^{+0.9}_{-0.7} \pm 0.5 \text{ MeV}/c^2$ , respectively. The difference between the mass

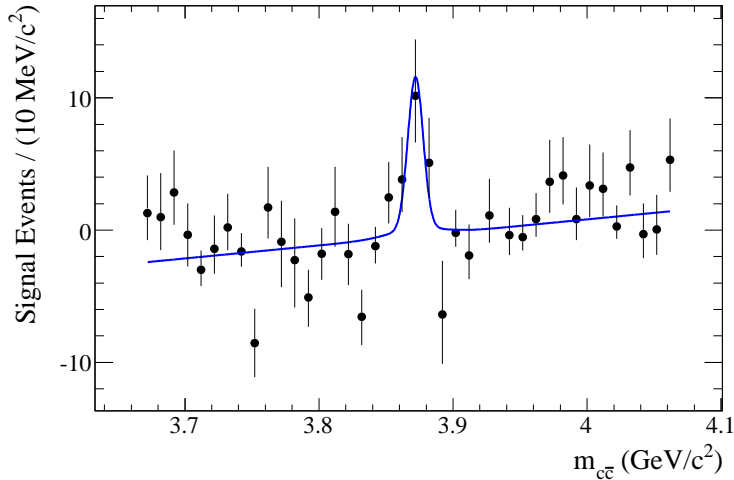


Figure 5: *The number of extracted signal events versus  $m_{c\bar{c}}$  for the  $X(3872)$  mass region. The solid curve represents the fit result.*

value obtained in the  $\bar{D}^{*0}D^0$  decay mode and that from PDG <sup>17)</sup> is then  $3.8^{+1.2}_{-2.0}$  MeV/c<sup>2</sup> from BELLE and  $3.7^{+1.1}_{-0.9}$  MeV/c<sup>2</sup> from *BABAR*, indicating that the effect is real. This mass difference has received a lot of attention, although a simple explanation involving one unit of orbital angular momentum (and hence  $J^P = 2^-$ ) has been proposed recently <sup>18)</sup>.

## 5 The $Y(3940)$

The  $Y(3940)$  was first observed by the BELLE collaboration <sup>19)</sup> in the decay process  $B \rightarrow J/\psi\omega K$  using  $253 \text{ fb}^{-1}$  of data. The mass and width obtained for this resonance were  $m = 3943 \pm 11 \pm 13 \text{ MeV}/c^2$  and  $\Gamma = 87 \pm 22 \pm 26 \text{ MeV}$ . In *BABAR* a data sample of  $348 \text{ fb}^{-1}$  is used to search for the  $Y(3940)$  <sup>20)</sup>. Charged and the neutral  $B$ -decays are analyzed separately, and in the *BABAR* analysis finer mass binning was used on the basis of mass resolution studies. Signal events were corrected for acceptance and mass resolution effects. A significant enhancement is observed near threshold in the charged mode, and a statistically-limited, but consistent, signal is obtained in the neutral mode.

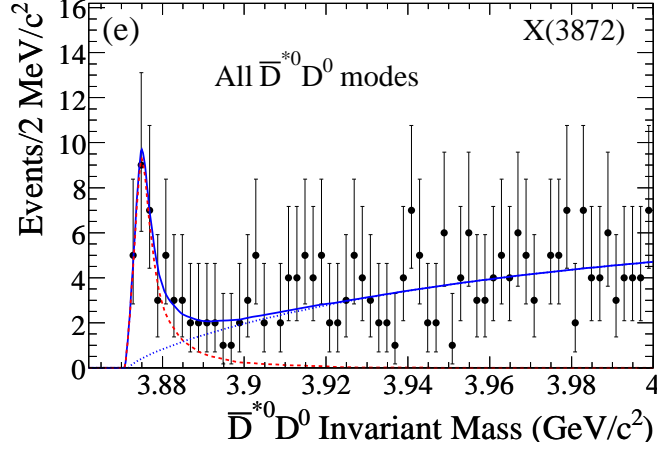


Figure 6: The  $\bar{D}^{*0}D^0$  invariant mass, where the solid curve shows the fit result and the dashed curves represent the signal and background contributions.

In Fig. 7 we show the acceptance-corrected  $J/\psi\omega$  mass distributions for the charged ( Fig. 7(a)) and neutral ( Fig. 7(b))  $B$  decay modes, respectively. The data points are fitted with a Breit-Wigner signal function and a single Gaussian function for the non-resonant contribution. Good fits to the data are obtained, as shown by the solid curves. The mass and width of the  $Y(3940)$  are found to be  $m = 3914.6_{-3.4}^{+3.8}(\text{stat})_{-1.9}^{+1.9}(\text{syst})$  MeV/ $c^2$  and  $\Gamma = 33_{-8}^{+12}(\text{stat})_{-5}^{+5}(\text{syst})$  MeV, respectively, with branching fractions for the charged and the neutral decay modes  $\mathcal{BF}(B^+ \rightarrow YK^+) = (4.9_{-1.0}^{+1.0}(\text{stat})_{-0.5}^{+0.5}(\text{syst})) \times 10^{-5}$ , and  $\mathcal{BF}(B^0 \rightarrow YK^0) = (1.5_{-1.2}^{+1.4}(\text{stat})_{-0.2}^{+0.2}(\text{syst})) \times 10^{-5}$ ; the latter has corresponding upper limit (95% C.L.)  $3.9 \times 10^{-5}$ .

## 6 Acknowledgments

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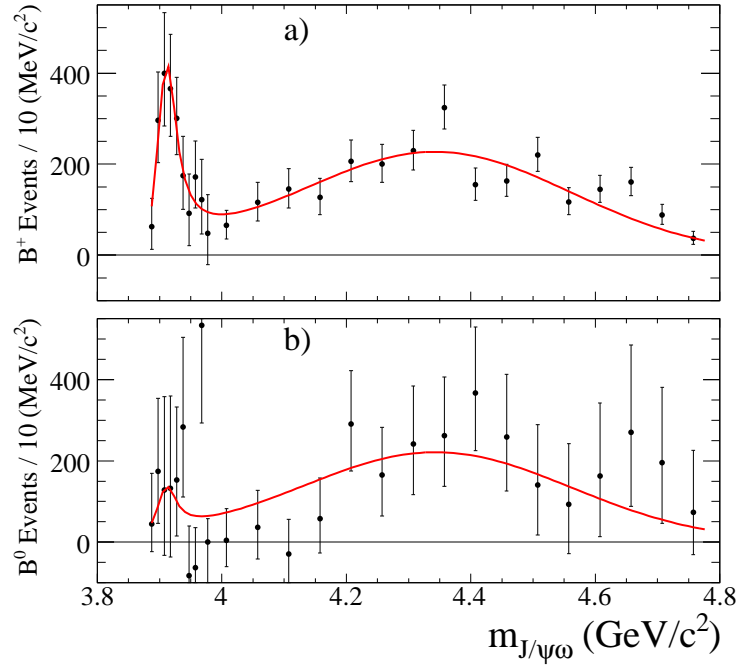


Figure 7: The acceptance-corrected  $J/\psi\omega$  mass distribution for (a)  $B^+$  and (b)  $B^0$  decay. The solid curves represent the fit results.



## References

1. S.-K. Choi *et al.*, Phys. Rev. Lett. **91**, 262001 (2003)
2. D. Acosta *et al.*, Phys. Rev. Lett. **93**, 072001 (2004)
3. V. M. Abazov *et al.*, Phys. Rev. Lett. **93**, 162002 (2004)
4. B. Aubert *et al.*, Phys. Rev. **D71**, 071103 (2005)
5. B. Aubert *et al.*, Phys. Rev. Lett. **95**, 142001 (2005)
6. B. Aubert *et al.*, Phys. Rev. **D 74**, 091103(R) (2006)
7. B. Aubert *et al.*, arXiv:0710.1371 [hep-ex], (2007)
8. B. Aubert *et al.*, Phys. Rev. **D 73**, 012005 (2006)
9. B. Aubert *et al.*, Phys. Rev. **D 73**, 011101 (2006)
10. B. Aubert *et al.*, Phys. Rev. Lett. **98**, 212001 (2007)
11. X. L. Wang *et al.*, Phys. Rev. Lett. **99**, 142002 (2007)
12. B. Aubert *et al.*, Phys. Rev. **D 71**, 031501 (2005)
13. B. Aubert *et al.*, Phys. Rev. **D 74**, 071101 (2006)
14. K. Abe *et al.*, arXiv:0505037 [hep-ex], (2005)
15. G. Gokhroo *et al.*, Phys. Rev. Lett. **97**, 162002 (2006)
16. B. Aubert *et al.*, arXiv:0708.1565 [hep-ex], (2007)
17. W.-M. Yao *et al.*, J. Phys. **G33**, 1 (2006)
18. W. Dunwoodie and V. Ziegler, arXiv:0710.5191 [hep-ex], (2007)
19. S.-K. Choi *et al.*, Phys. Rev. Lett. **94**, 182002 (2005)
20. B. Aubert *et al.*, arXiv:0711.2047 [hep-ex], (2007)